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50 important research questions in microbial ecology

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MICROBIAL ECOLOGY GROUP

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1 **50 important research questions in microbial ecology**

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33 39 environmental processes, evolutionary processes, functional diversity, host-microbiome interactions,
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35 40 priority setting, research agenda
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41 **Abstract**

42 Microbial ecology provides insights into the ecological and evolutionary dynamics of microbial
43 communities underpinning every ecosystem on Earth. Microbial communities can now be investigated
44 in unprecedented detail, although there is still a wealth of open questions to be tackled. Here we
45 identify 50 research questions of fundamental importance to the science or application of microbial
46 ecology, with the intention of summarising the field and bringing focus to new research avenues.
47 Questions are categorised into seven themes: Host-Microbiome Interactions; Health and Infectious
48 Diseases; Human Health and Food Security; Microbial Ecology in a Changing World; Environmental
49 Processes; Functional Diversity; and Evolutionary Processes. Many questions recognise that
50 microbes provide an extraordinary array of functional diversity that can be harnessed to solve real-
51 world problems. Our limited knowledge of spatial and temporal variation in microbial diversity and
52 function is also reflected, as is the need to integrate micro- and macro-ecological concepts, and
53 knowledge derived from studies with humans and diverse other organisms. Certain methods remain
54 inadequate and currently limit progress in the field. Although not exhaustive, the questions presented
55 are intended to stimulate discussion and provide focus for researchers, funders, and policy makers,
56 informing the future research agenda in microbial ecology.

57

58 Introduction

59 In recent years, there has been an explosion in microbial ecological research, which is reflected in
60 broad-scale research projects such as the Human Microbiome Project and the Earth Microbiome
61 Project, as well as in the peer-reviewed literature (e.g. Boers *et al.*, 2016). Recent rapid technological
62 advances, including next-generation sequencing, (meta)genomics, metabolomics,
63 (meta)transcriptomics and (meta)proteomics, have vastly increased our ability to study microbial
64 community complexity and function (Morris *et al.*, 2002; Hiraoka *et al.*, 2016). These provide
65 unprecedented opportunities to assess genomic potential, gene regulation, expression and function *in*
66 *situ* (Schneider *et al.*, 2012, Franzosa *et al.*, 2015), especially when combined with detailed knowledge
67 of natural history and environmental parameters (Peay, 2014). Such techniques have been applied to
68 a vast range of fields within the scope of 'microbial ecology' in order to better understand how
69 microorganisms interact with and affect their environment, each other, and other organisms.

70 With an overwhelming and ever-growing number of potential and critical research avenues in
71 microbial ecology, it is timely to identify major questions and research priorities that would progress
72 the field. Here we present the results of a workshop hosted by the British Ecological Society's
73 Microbial Ecology Special Interest Group in June 2016, which used a discussion and voting-based
74 system to identify 50 research questions of importance to the field of microbial ecology. Similar
75 exercises identifying important research questions have been conducted in conservation (Sutherland
76 *et al.*, 2009, Dicks *et al.* 2012), pure ecology (Sutherland *et al.*, 2013a), marine biodiversity (Parsons
77 *et al.*, 2014), sustainability (Dicks *et al.*, 2013; Jones *et al.* 2014), and non-ecological subjects
78 including UK poverty (Sutherland *et al.*, 2013b). These papers have been widely accessed and are
79 directly applicable to the development of policy, as highlighted by Jones *et al.* (2014).

82 Methods

83 Participants

84 The methods used here were based broadly on those presented in Sutherland *et al.* (2011). A one-day
85 workshop was held by the British Ecological Society's Microbial Ecology Special Interest Group at the
86 University of Salford (UK) in June 2016. Invitations to attend the meeting were distributed via the

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87 British Ecological Society's membership mailing list and through social media (Twitter and Facebook).
88 In total, 34 participants from 20 institutions attended and contributed to the development of the 50
89 questions listed below, with the majority listed as authors on this paper.

90

91 *Questions*

92 Prior to the workshop, attendees were asked to submit questions via an online form that they thought
93 most closely met the following brief:

94 "We are aiming to identify 50 questions that, if answered, will make a considerable
95 difference to the use of microbial ecology by practitioners and policy makers, or to
96 the fundamentals of the field of microbial ecology. These should be questions that
97 are unanswered, could be answered, and could be tackled by a research
98 programme. This is expected to set the agenda for future research in the field of
99 microbial ecology."

100

101 A total of 244 questions were submitted by attendees (see Supplementary Information), and assigned
102 (by R.E. Antwis and S.M. Griffiths) to the following themes;

- 103 1) *Host-Microbiome Interactions*;
104 2) *Health and Infectious Diseases*;
105 3) *Human Health and Food Security*;
106 4) *Microbial Ecology in a Changing World*;
107 5) *Environmental Processes*;
108 6) *Functional Diversity*;
109 7) *Evolutionary Processes*.

110

111 An additional eighth theme named '*Society and Policy*' was created to capture a number of questions
112 that were generally applicable across the biological sciences, as well as a number of questions

113 specific to the field of microbial ecology which could not necessarily be addressed through laboratory
114 based microbial ecology research, *per se*.

115

116 *Question selection process*

117 Prior to the workshop, participants were asked to identify the top ~20% of questions in each theme
118 that most closely aligned with the brief (selection of 5-11 questions from a total of 26-57 questions per
119 theme via online form; Supplementary Information). Participants were asked to consider all questions
120 within a theme and to select questions based on the theme's context and the brief for the workshop.
121 Some questions were included in more than one theme to encourage discussion and to increase the
122 likelihood that pertinent questions remained in the selection process. Questions were then ranked
123 according to the number of online votes they received, and this formed the material for the workshop.

124 Three sets of parallel sessions were run at the workshop, with participants free to select which
125 theme sessions they attended. Questions were discussed in order of lowest ranking to highest, with
126 duplicates removed and questions reworded as necessary. For each theme, a final set of 'gold' (~15%
127 of questions, total of 47 questions across all themes) and 'silver' questions (~10% of questions, total of
128 29 questions) were identified. Where necessary, a show of hands was used to ensure the democratic
129 process was upheld.

130 A final plenary session was held in which all gold and silver questions were discussed. For
131 gold questions, duplicates among categories were removed and questions reworded to reflect the
132 discussion in the room, resulting in 43 gold questions. A similar process was then completed for silver
133 questions, and a show of hands used to vote for seven questions that could be elevated to gold status
134 to form the final set of 50 questions.

135

136 *Limitations*

137 All but four participants were from British universities, although there were representatives from a
138 range of nationalities and research areas. The manner in which this paper was developed (*i.e.* through
139 a physical workshop and via the British Ecological Society) means that, without a substantial travel
140 budget, a bias towards UK institutions was inevitable. However, many participants have worked on, or

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2
3 141 currently collaborate in, research projects on non-UK ecosystems and species, and therefore the
4 142 questions proposed are drawn from considerable knowledge and experience of the field
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6 143 internationally. Additionally, although most individuals were from academic institutions, many
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8 144 individuals had previous or on-going collaborations with industrial partners and governmental/non-
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10 145 governmental organisations.
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15 147 **Results**

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17 148 The following 50 questions are presented by theme, and are not ordered according to relevance or
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19 149 importance. Due to the nature of the process, some questions may appear similar across themes, but
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21 150 within the context of each theme can take on a different meaning. Some questions may relate to
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23 151 research areas that are already somewhat active, and these serve to highlight the importance of and
24
25 152 encourage further work in these areas. Some of these questions apply across multiple biomes and
26
27 153 ecosystems, and can be considered in the context of multiple host organisms and across varying
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29 154 temporal and spatial scales.
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33 156 ***Host-Microbiome Interactions***

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35 157 Host-microbiome interactions determine many host life history traits such as behaviour, reproduction,
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37 158 physiological processes, and disease susceptibility (Archie and Theis, 2011; Willing *et al.*, 2011; Koch
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39 159 & Schmidt-Hempel, 2011; Daskin & Alford, 2012; King *et al.*, 2016). Increasingly, we are discovering
40
41 160 that host-microbiome interactions produce complex and dynamic communities that fluctuate in
42
43 161 compositional abundance correlated with factors as diverse as host genotype, developmental stage,
44
45 162 diet, and temporal changes, among others (e.g. Spor *et al.*, 2011). Even in otherwise well studied
46
47 163 organisms, very little is known about the consequences of microbiome variation for host processes,
48
49 164 particularly across different spatial and temporal scales. Considerations of host microbiomes are also
50
51 165 likely important for global issues, such as the efficacy of conservation efforts including species
52
53 166 reintroduction programmes (reviewed in Redford *et al.*, 2012; McFall-Ngai, 2015). Additionally,
54
55 167 interactions between native and non-native species are correlated with transmission of microbiota,
56
57 168 often determined by relatedness or diet type (Ley *et al.*, 2008), and the microbiome plays a key role in
58
59 169 the control and competence of insect crop pests and vectors of disease (reviewed in Weiss & Aksoy,
60

170 2011). The following questions aim to address the shortfall in our understanding of the interactions
171 between microbiomes and their human and non-human hosts.

172

173 1. What are the primary mechanisms within a host that mediate microbe-microbe and host-microbe
174 interactions?

175 2. What are the relative contributions of host-associated and environmental factors in determining host
176 microbial community composition?

177 3. How do microbial communities function to affect the phenotype of the host?

178 4. Can compositional or evolutionary changes in microbiomes help hosts adapt to environmental
179 change within the lifetime of the host?

180 5. What is the role of the microbiota in host speciation processes?

181 6. How can the associated microbiota be effectively included in risk assessments of Invasive Non-
182 Native Species?

183 7. How does the microbiome of captive animals affect the success of reintroduction programmes?

184 8. How can a 'systems biology' approach improve our understanding of host-microbe interactions?

185

186 ***Health and Infectious Diseases***

187 The last 50 years have seen the emergence of several hypervirulent wildlife pathogens in animals
188 (e.g. Tasmanian devil face tumour disease, avian malaria, amphibian chytridiomycosis; reviewed in
189 Tompkins *et al.*, 2015) and plants (e.g. sudden oak and larch death, ash dieback; Pautasso *et al.*,
190 2015). Although the role of microorganisms as pathogens is well known, the importance of host-
191 associated microbiomes in regulating disease susceptibility is becoming more apparent (Koch &
192 Schmidt-Hempel, 2011; Daskin & Alford, 2012; King *et al.*, 2016). A major outstanding research goal is
193 to understand how within-host interactions among microbes and invading pathogens may shape
194 patterns of infection intensity and disease progression (see also *Evolutionary Processes*). Several
195 studies have sought to determine how manipulation of host microbiomes may ameliorate the spread
196 and impact of such diseases (e.g. Rebollar *et al.*, 2016).

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3 197 While for many disease states the paradigm holds true that one microorganism causes one
4 198 disease, polymicrobial infections are becoming more apparent through metagenomic and
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6 199 metatranscriptomic sequencing of disease-associated microbial communities (Gilbert *et al.*, 2016).
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8 200 Consequently, the 'pathobiome' concept, where a disease state is influenced by complex interactions
9
10 201 between commensal and pathogenic microorganisms, presents new challenges for applying Koch's
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12 202 postulates to diseases arising from polymicrobial interactions (Vayssier-Taussat *et al.*, 2014), such as
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14 203 black band disease (BBD) in corals (Sato *et al.*, 2016) and olive knot disease (Buonaurio *et al.*, 2015).

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16 204 In this theme we have identified research questions relating to the microbial ecology of
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18 205 infectious diseases and host health. Although much can be learnt from the comparatively high number
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20 206 of studies in the human and biomedical literature (e.g. using network approaches in epidemiology), the
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22 207 questions selected in this theme predominantly relate to non-human animals and plants, as humans
23
24 208 are covered later ('Human Health and Food Security').

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28 210 9. How can we better track the source and dispersal of particular microorganisms in real time?
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30 211 10. Many microorganisms are unculturable, and many microbiome studies reveal that diseases are
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32 212 polymicrobial; how can we re-evaluate Koch's postulates in this context?
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34 213 11. Which factors trigger 'covert' infections to become 'overt', impacting host health?
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36 214 12. At the population level, how is the burden and shedding intensity of intracellular microbes affected
37
38 215 by co-infection by extracellular parasites?
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40 216 13. What is the ecological relevance of the internalization of bacterial pathogens by protozoa in terms
41
42 217 of their survival and spread?
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44 218 14. How can network theory best be used to predict and manage infectious disease outbreaks in
45
46 219 animals and plants?
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48 220 15. Can microbiomes of wildlife (plants and animals) be used or manipulated to enhance health and/or
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50 221 disease resistance?
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56 223 **Human Health and Food Security**
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224 With the human population due to exceed eight billion by 2024, food security and human health are
225 high on political and scientific agendas. The human microbiome has been the focus of intense
226 research efforts in recent years, (e.g. Walter & Ley, 2011; Spor *et al.*, 2011; Mueller *et al.*, 2012),
227 because gut symbionts shape the immune response (Round *et al.*, 2009), and diversity fluctuates
228 through chronic conditions and infectious diseases including diabetes, obesity (Serino *et al.* 2016;
229 Baothman *et al.*, 2016; Ridaura *et al.*, 2013), asthma (Smits *et al.* 2016), and HIV (Lozupone *et al.*,
230 2013). Improving our understanding of the core human microbiome and individual variation will
231 underpin pharmomicrobiomics, enabling development of novel therapeutic treatments and, ultimately,
232 personalised medicine (e.g. Ubeda *et al.*, 2013).

233 Antibiotic resistance resulting from selective pressures generated by the use and misuse of
234 antibiotics is a global threat to public health (Levy, 1997; Tam *et al.*, 2012). The volume of antibiotics
235 used in agriculture now exceeds the amount used in human medicine in many countries (WHO, 2011).
236 Antibiotics are still widely used in livestock for prophylaxis and growth promotion, often at sub-
237 therapeutic concentrations, exacerbating resistance (Krishnasamy *et al.*, 2015). The impact of the
238 leaching of antibiotics into the natural environment and subsequent impacts on natural microbial
239 communities remains poorly characterised (Franklin *et al.*, 2016). Current practices of growing high-
240 intensity monoculture crops have a negative impact on the microbial biodiversity of soils through a
241 combination of tillage, subsequent erosion and chemical applications (Helgason *et al.*, 1998; Jacobsen
242 and Hjelmsø, 2014; Zuber and Villamil, 2016), which imposes selection pressures on pathogenic
243 microbes, fungal symbiotic partners and plant growth promoting bacteria (Chapparo *et al.*, 2012;
244 Hartmann *et al.*, 2015). Thus, there is a need to maintain and enhance microbial populations of crop
245 ecosystems, especially in light of antibiotic resistance (Ellouze *et al.*, 2014). As antibiotic resistance
246 increases, along with our concern about potential impact on both human and animal health, there is an
247 increasing drive to find new forms of antibiotics.

248 Though the remit for this section is relatively broad, the questions focus on two central
249 themes: i) studying the human microbiome to improve the treatment of disease, including the
250 development of personalized medicine and novel antibiotics; and ii) understanding how *current*
251 antibiotic regimes and farming practices may negatively impact the diversity of the environmental
252 microbiome and food production capacity.

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- 254 16. How can human microbiome studies improve personalised medicine?
- 255 17. What ecological principles can be applied in the search for new antibiotics and alternatives?
- 256 18. What are the main determinants of waterborne infection outbreaks, and what is the best strategy
257 to control these in water distribution systems?
- 258 19. What are the consequences of antibiotic and pharmaceutical use in human medicine on microbial
259 communities in freshwater and soil environments?
- 260 20. To what extent are microbial species distributions influenced by climate, and what are the
261 consequences for food security and human health?
- 262 21. How much microbial diversity in the soil has been lost through monoculture and what is the
263 importance of this?
- 264 22. Intensive farming may involve high levels of agrochemicals and broad-spectrum antibiotic usage -
265 what will be the long-term effects on microbial communities?
- 266 23. How best can we harness microbial communities to enhance food production?

267

268 ***Microbial Ecology in a Changing World***

269 Global changes resulting from human activity impact almost every habitat on earth. It is imperative that
270 we focus efforts on understanding the impacts of human activities such as climate change,
271 urbanisation, agriculture, and industrial processes on microbial communities, ecosystem functioning
272 equilibrium, and host health. Microbial populations have a tremendous capacity to adapt to changes in
273 their abiotic environment, yet the functional implications of these transitions in microbial ecology are
274 still poorly understood and characterised (Bissett *et al.*, 2013), and the role of microbes in mediating
275 the response of larger organisms to change is equally understudied. Global environmental changes
276 (GECs) are complex and multifaceted. Human activities such as urbanisation, land-use change and
277 introduction of invasive species have played a role in shifting global ecosystems via desertification,
278 climate change and habitat degradation. Although such changes have been quantified in aquatic and
279 terrestrial habitats (*e.g.* Haberl *et al.*, 2007; Halpern *et al.*, 2008), their effects on microbial
280 communities and impacts on ecosystem function are often hindered by a lack of characterisation of
281 communities, or limited understanding of microbial functional traits. Shifts in basic nutrients and gases

such as CO₂, along with temperature fluctuations and water availability, greatly influence the distribution and behaviour of species (Tylianakis *et al.*, 2008). GECs can alter host fitness or ecosystem functioning (Shay *et al.*, 2015; Webster *et al.* 2016) and are likely to occur in combination. While there is a great deal of research into the effects of each of these on microbial communities (Schimel *et al.*, 2007; Shurin *et al.*, 2012; Lloret *et al.*, 2014), literature considering the effect of multiple GECs is sparser, and these have complicated and often unpredictable consequences when combined (although see Hutchins *et al.*, 2009; Ryalls *et al.*, 2013). In this section, we consider how human activities directly and indirectly influence the microbial world. Where applicable, these questions can be considered across multiple biomes and ecosystems, with reference to resulting trophic cascades, in addition to the impacts on multiple biogeochemical processes. We also consider how microbes can be used as a tool for mitigation or bioremediation of human-induced environmental changes, and the ways in which microbes can be included in current evaluations of global change.

294

295 24. How can we integrate microbial communities into models of global change?

296 25. Will ocean acidification, temperature increases and rising sea levels lead to changes in microbial diversity or function, and what will the cascading effects of this be?

298 26. How do human activities, such as oil and gas drilling, influence the sub-surface microbiome(s)?

299 27. How will increasing urbanisation affect environmental and host-associated microbial communities?

300 28. How resilient are different microbial functional groups to ecosystem disturbance?

301 29. Can we manipulate microbial succession in species-poor soils to encourage repopulation by flora and fauna?

303

304 ***Environmental Processes***

305 Microbes play a fundamental role in environmental processes and ecosystem services, including nutrient cycling and organic matter decomposition (Chin *et al.* 2016; Creamer *et al.*, 2015; Weider *et al.*, 2013), bioremediation of contaminated habitats or waste systems (Haritash & Kaushik, 2009; Oller *et al.*, 2011), and influencing greenhouse gas emissions (Singh *et al.*, 2010; Bragazza *et al.*, 2013; Hu *et al.*, 2015). The ability to harness these processes has great potential for societal and environmental

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3 310 applications, particularly in extremophiles, which frequently reveal metabolic capabilities and
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5 311 evolutionary solutions not witnessed elsewhere in the microbial world (Coker et al. 2016). However, it
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7 312 is rarely possible to directly link the presence of a specific microbial taxon to a particular ecological
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9 313 process. Other methodological challenges include establishing the relative importance of biotic and
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11 314 abiotic factors in microbial ecosystem function, and determining the appropriate spatial and temporal
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13 315 scale necessary to discriminate links between microbiota and their ecological functions (Bissett *et al.*,
14
15 316 2013). Concurrently, a deeper understanding is required of human-induced impacts on the global
16
17 317 microbiome through urbanisation, habitat degradation, climate change, and the introduction of invasive
18
19 318 species, amongst others.
20
21 319
22
23 320 30. How do we successfully establish microbial communities used in bioremediation?
24
25 321 31. How important is the rare microbiome in ecosystem function, and how does this change with
26
27 322 stochastic events?
28
29 323 32. To what extent is microbial community diversity and function resilient to short- and long-term
30
31 324 perturbations?
32
33 325 33. What is the importance of spatial and temporal variation in microbial community structure and
34
35 326 function to key environmental processes and geochemical cycles?
36
37 327 34. How can we accurately measure microbial biomass in a reproducible manner?
38
39 328 35. Which mechanisms do extremophiles use for survival and how can they be exploited?
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43
44 330 **Functional Diversity**

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46 331 Ecologists are increasingly turning their attention to classifying species based on their activity
47
48 332 (function) within an ecosystem, rather than their genotype (Crowther *et al.*, 2014). This is particularly
49
50 333 relevant for microbial ecology, in which species are hard to define, horizontal gene transfer is rife, and
51
52 334 taxonomy is often blurred. Understanding how membership within complex and dynamic microbial
53
54 335 communities relates to the function of that community is one of the key challenges facing microbial
55
56 336 ecology (Widder *et al.*, 2016). This is true across a vast range of spatial scales, from microbial dyads
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58 337 to the gut of a *Drosophila* fly, to ancient trees and their associated ecosystems, right through to global
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338 biogeochemical processes. There is an urgent need to understand how the genome of a microbial
339 community (and in some cases, its host) relates to metabolic capacities. Conversely, there is also a
340 need to understand how ecosystems depend on a particular organism or group of organisms for any
341 given process and function. This section describes the need to move from simply describing microbial
342 diversity to understanding what these organisms are doing, how they are doing it, and what biotic and
343 abiotic drivers are controlling their activity. Each question may derive a suite of different answers,
344 depending on the group of organisms, the habitat and the process.

345

346 36. What are the mechanisms driving microbial community structure and function, and are these
347 conserved across ecosystems?

348 37. What is the relative importance of stochastic vs. determinative processes in microbial community
349 assembly?

350 38. How conserved are microbial functions across different spatial and temporal scales?

351 39. What is the relative importance of individual 'species' for the functioning of microbial communities?

352 40. How much functional redundancy is there in microbial communities, and how does functional
353 redundancy affect measures of diversity and niche overlap?

354 41. How often are functional traits of microbes successfully conferred through horizontal gene
355 transfer?

356 42. What methods can we use to marry microbial diversity with function; how do we link
357 transcriptomics, proteomics and metabolomics?

358 43. How do we move beyond correlation to develop predictive models that advance our understanding
359 of microbial community function and dynamics?"

360 44. How useful are synthetic communities for testing theories about microbial community dynamics
361 and function?

362

363 ***Evolutionary Processes***

364 The role of microorganisms in determining evolutionary outcomes of hosts is being investigated in

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3 365 increasing detail (McFall-Ngai *et al.*, 2013). Experimental evolution studies represent a powerful
4 366 means of quantifying host-microbe and microbe-microbe coevolution, and have highlighted the
5
6 367 extraordinary capacity of microbes to act as key mediators of host fitness (e.g. King *et al* 2016). Whilst
7
8 368 experimental coevolution studies provide a framework for linking dyadic interactions to community-
9
10 369 scale dynamics (Brockhurst & Koskella, 2013), evolutionary principles stemming from macro-ecology
11
12 370 are being applied to microbial communities of humans (Robinson *et al.*, 2010). However, fundamental
13
14 371 biological questions that are well-studied in macrobiology remain controversial for microbial ecology,
15
16 372 for example the species concept remains a source of debate (Freudenstein *et al.* 2016). The
17
18 373 operational taxonomic unit (OTU) has become the standard unit for identifying bacteria at the highest
19
20 374 taxonomic resolution possible, yet it is hard to clearly define where taxonomic boundaries lie between
21
22 375 two bacteria, and what an OTU really represents in biological terms. This is especially problematic in
23
24 376 the context of horizontal gene transfer, which is commonly observed in bacteria and has turned our
25
26 377 understanding of evolutionary processes upside down. This section relates to how general ecological
27
28 378 principles influence microbial evolution and *vice versa*, what this means for global biodiversity, and
29
30 379 whether evolutionary principles can be utilised for anthropogenic gain.

- 31 380
32
33 381 45. How can a bacterial 'species' be defined?
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35 382 46. To what extent is faunal and floral biodiversity influenced by microbial communities?
36
37 383 47. To what extent do microbial communities have an equivalent to keystone 'species'?
38
39 384 48. Does the structure of microbial communities conform to the same ecological rules/principles as in
40
41 385 other types of communities?
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43 386 49. How do fundamental shifts in environmental conditions impact the trajectory of microbial
44
45 387 evolution?
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47 388 50. What are the relative selective forces favouring microbial genome expansion or reduction?
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51 389 **Society and Policy**
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53 390 We need to find ways to apply fundamental biological research to the benefit of society and policy. For
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55 391 example, collaboration with social scientists is crucial when investigating public understanding of
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57 392 microbial ecology, as well as using citizen science approaches to tackle microbial ecology research
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questions. Many questions relating to this area were discussed at the workshop, and here we present four additional questions that were developed at the meeting that relate to societal and policy-based aspects of microbial ecology.

- How can we best address supply and demand of information about microbial ecology between researchers, clinicians, policy makers and practitioners?
- How can we best use social and traditional mass media for early identification of emerging threats to animal and plant health?
- How can we develop an open access data repository or integrate existing databases to create a centralised and standardised method for data and methods sharing in microbial ecology?
- How can we replace fear-based regulation with risk-based regulation, specifically with regard to the use of microbes in bioremediation and bioaugmentation?

Discussion

Here we present 50 important research questions across a number of themes relating to the field of microbial ecology. Although there are many other research issues worthy of investigation, it is intended that these questions will be used to inform and direct future research programmes and agendas, particularly in areas where microbial ecology has not previously been considered or applied. In many cases, these questions are deliberately broad to allow researchers to adapt them to their own areas of interest, for example across different systems, or to varying spatial scales. Across many questions there was strong recognition of the vast metabolic capabilities of microorganisms and microbial communities, and the need to harness this power to improve human and animal health and wellbeing. Some themes addressed various existing mechanisms for exploiting microbial processes, namely bioremediation, soil improvement, water treatment and probiotic suppression of pathogen resistance. As these are already active areas of research, the questions posed here are structured to provide a framework by which these efforts can be directed in the future.

A predominant theme that emerged was the need to integrate knowledge between different research areas, for example the application of information from human microbiome studies to the

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2
3 421 study of other non-model host organisms, and the potential to apply macro-ecological frameworks to
4 422 micro-ecological concepts. Many fundamental biological questions that are well-studied in classical
5 423 ecology remain controversial for microbial ecology, and the species concept (Freudenstein *et al.*
6 424 2016), taxonomy, and how the OTU should be defined for microorganisms, generated multiple
7 425 questions (e.g. see '*Evolutionary Processes*' theme). Classical community ecology concepts should
8 426 not be overlooked when considering microbial dynamics (Rynkiewicz *et al.*, 2015) and, conversely,
9 427 microbial communities may prove useful models for general ecology due to their short generation
10 428 times, reproducibility, and ease of use in the laboratory environment (Brockhurst & Koskella, 2013;
11 429 Libberton *et al.*, 2015; King *et al.*, 2016). There have been a number of calls for the medical profession
12 430 to look to ecological and evolutionary tools when seeking to understand epidemiology (Johnson *et al.*,
13 431 2015), investigating novel antibacterial agents (Vale *et al.*, 2016), and considering multi-host, multi-
14 432 agent disease systems (Buhnerkempe *et al.*, 2015).

15
16 433 The '*Host-Microbiome Interactions*' theme considered the need to understand factors
17 434 influencing microbiome composition, which in turn have consequences for a myriad of host traits,
18 435 including disease susceptibility and host evolution (Chisholm *et al.*, 2006; Archie & Theis, 2011; Spor
19 436 *et al.*, 2011; Cho & Blaser, 2012; McFall-Ngai *et al.*, 2013; McFall-Ngai, 2015; Zilber-Rosenberg &
20 437 Rosenberg, 2008). As this theme considered microbiota from the perspective of the host, there was
21 438 some overlap with the '*Health and Infectious Diseases*' and '*Evolutionary Processes*' themes.
22 439 Probiotics were discussed as a viable and promising alternative to current strategies in a number of
23 440 contexts in these themes, not only to improve individual health, but also to decrease disease
24 441 susceptibility of humans and other animals, to enhance nutritional quality of food, and to mitigate the
25 442 negative impacts of antibiotic use across humans, livestock, aquaculture and agriculture (Martín *et al.*,
26 443 2013; Newaj-Fyzul *et al.*, 2014; Smith, 2014; Fox, 2015). Developing personalized probiotic-based
27 444 therapies requires complementary diversity and functional-based studies in order to elucidate the
28 445 specific roles of microbiota in health and disease, and thus how microbial communities can be
29 446 manipulated.

30
31 447 Questions considered in both the '*Functional Diversity*' theme and the '*Environmental*
32 448 *Processes*' theme raised a common need to understand changes in microbial community structure
33 449 and function across spatial and temporal scales (Carmona *et al.*, 2016). Establishing appropriate
34 450 spatial scales for studying microbial processes is an outstanding challenge: micro-organisms can

orchestrate ecosystem functioning across whole biomes (Sheffer *et al.*, 2015), yet fungi exhibit low mobility on tree barks (Koufopanou *et al.* 2006, Robinson *et al.*, 2016), and an air void in soil can be an insuperable barrier for a bacterium. Similarly, drawing meaningful conclusions about microbial processes requires understanding of their temporal variability; for example, diurnal influences (Shurpali *et al.*, 2016), or lags behind changes in ecosystem drivers (Allison and Martiny, 2008).

A subject common to a number of themes was the role of individual species *versus* consortia in community functioning. The question of defining bacterial species is a contentious topic, and the issue remains whether some microbial taxa act as keystones in ecosystem functions. Many microbial surveys carry the implicit assumption that the most abundant taxa are also the most important, yet rare species can be hugely significant if they are highly active and/or monopolise a particular process (Lynch and Neufeld, 2015). The collective metabolic capabilities of micro-organisms have great potential for *in situ* applications such as bioremediation, particularly when used in multi-species consortia (Mikesková *et al.*, 2012). Successful bioremediation and environmental management requires the introduction of new assemblages into an established community, or stimulation of key members of the community *in situ* (Rillig *et al.*, 2015). In turn, predicting the successful establishment of deliberately introduced organisms depends on an understanding of the principles underlying microbial community formation and structure. Despite these challenges, functional diversity modelling has successfully been applied to the ecological restoration of some plant communities (Laughlin, 2014). Closely linked to this is the issue of functional redundancy, and to what extent it is possible to lose species without affecting ecosystem functions. Already there is evidence that microbial communities may be less functionally redundant than macro-organism communities (Delgado-Baquerizo *et al.*, 2016). This issue ties into fundamental ecological concepts, such as niche theory (Carmona *et al.*, 2016); if multiple organisms are carrying out the same process, apparently interchangeably, how do they avoid competitively excluding one another? The concept of keystone species has been shown to be applicable to microbes (Neufeld *et al.*, 2008; Pester *et al.*, 2010; Ze *et al.*, 2012; Yu *et al.*, 2016), yet further work is needed to characterise the extent to which keystone functions occur in different environments and whether these can be consistently identified (Anderson, 2003; Pester *et al.*, 2010).

The need for open access databases and repositories, both in the context of data sharing as well as for methods and protocols, was reflected in the questions shortlisted for the 'Society and

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3 481 *Policy*' theme. Discussions included the benefits of forming collaborative and open research
4 482 communities, and the need to ensure the legacy of academic research through improving regulation
5 483 and policy and engagement with the public. Fear-based regulation of research, grounded in alarmist or
6 484 populist campaigns, as opposed to risk-based regulation built upon evidence, was identified as a
7 485 possible obstacle to progress, which could be addressed through greater interaction between
8 486 microbial ecologists and the public at both governmental and grass roots levels. Large scale
9 487 assessments of ecosystem services and degradation acknowledge the paucity of data on microbial
10 488 impacts, presumably because there are no convincing large-scale messages that can be derived at
11 489 this stage (Norris *et al.*, 2011). Microbial diversity is therefore rarely considered when estimates of
12 490 biodiversity are required for policy or management decisions. That said, the increasing recognition of
13 491 the fundamental impact of the microbial world on the functioning of larger-scale processes has made
14 492 the deliberate manipulation of the microbial world a controversial subject, which was reflected in the
15 493 number of draft questions submitted related to bioremediation and bioaugmentation (see
16 494 Supplementary Information). Collaboration with social scientists was identified as crucial in gauging
17 495 the public understanding of microbial ecology, and citizen science approaches were considered as
18 496 tools to tackle key microbial ecology research questions.

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33 497 The 50 questions identified here cover a broad range of topics, but some over-arching themes
34 498 recur across multiple questions, including a recognition that microbes play an important role in a
35 499 variety of different processes and systems, which may be harnessed to solve real-world problems.
36 500 There were some similarities between the questions identified here and those identified by previous
37 501 workshops of a similar nature. For example, questions relating to soil health and biodiversity (Dicks *et*
38 502 *al.* 2013), a requirement for developing a theoretical understanding of micro- and macro- ecological
39 503 concepts (Prosser *et al.* 2007, Sutherland *et al.* 2013a) and disease dynamics (Prosser *et al.* 2007,
40 504 Sutherland *et al.* 2013a) have a degree of commonality with this list. This indicates that the ecological
41 505 theory underpinning many research questions transcends scientific disciplines, and that there is still
42 506 much work to be done at both theoretical and applied levels. Within these 50 questions, we have tried
43 507 to provide a focus for researchers addressing scientific questions from a microbial perspective,
44 508 regardless of their background. It is expected that these questions will facilitate interesting discussion
45 509 and new, exciting, interdisciplinary research. The list is by no means exhaustive, and we recognise
46 510 that the questions presented here are relatively community-centric, primarily due to the recent

expansion in methodological approaches that have improved our understanding of microbial community diversity and function. That said, other areas of microbial ecology should not be ignored or forgotten. Given the rapidly evolving field of microbial ecology, it is expected that future workshops with a wide draw will be held to ensure that the identification of research priorities and areas of interest is a continuing process.

516

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524

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For Peer Review

50 important research questions in microbial ecology

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31 38 Keywords:
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33 39 environmental processes, evolutionary processes, functional diversity, host-microbiome interactions,
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35 40 ~~methods,~~ priority setting, research agenda
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Abstract

Microbial ecology provides insights into the ecological and evolutionary dynamics of microbial communities underpinning every ecosystem on Earth. Microbial communities can now be investigated in unprecedented detail, although there is still a wealth of open questions to be tackled. Here we identify 50 research questions of fundamental importance to the science or application of microbial ecology, with the intention of summarising the field and bringing focus to new research avenues. Questions are categorised into eight seven themes: Host-Microbiome Interactions; Health and Infectious Diseases; ~~Food Security and Human Health~~ and Food Security; Microbial Ecology in a Changing World; Environmental Processes; Functional Diversity; and Evolutionary Processes; ~~and~~ Methods in Microbial Ecology. Many questions recognise that microbes provide an extraordinary array of functional diversity that can be harnessed to solve real-world problems. Our limited knowledge of spatial and temporal variation in microbial diversity and function is also reflected, as is the need to integrate micro- and macro-ecological concepts, and knowledge derived from studies with humans and diverse other organisms. Certain methods remain inadequate and currently limit progress in the field. Although not exhaustive, the questions presented are intended to stimulate discussion and provide focus for researchers, funders, and policy makers, informing the future research agenda in microbial ecology.

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59 **Introduction**

60 In recent years, there has been an explosion in microbial ecological research, which is reflected in
61 broad-scale research projects such as the Human Microbiome Project and the Earth Microbiome
62 Project, as well as in the peer-reviewed literature (e.g. Boers *et al.*, 2016). Recent rapid technological
63 advances, including next-generation sequencing, (meta)genomics, metabolomics,
64 (meta)transcriptomics and (meta)proteomics, have vastly increased our ability to study microbial
65 community complexity and function (Morris *et al.*, 2002; Hiraoka *et al.*, 2016). These provide
66 unprecedented opportunities to assess genomic potential, gene regulation, expression and function *in*
67 *situ* (Schneider *et al.*, 2012, Franzosa *et al.*, 2015), especially when combined with detailed knowledge
68 of natural history and environmental parameters (Peay, 2014). Such techniques have been applied to
69 a vast range of fields within the scope of ‘microbial ecology’ in order to better understand how
70 microorganisms interact with and affect their environment, each other, and other organisms.

71 With an overwhelming and ever-growing number of potential and critical research avenues in
72 microbial ecology, it is timely to identify major questions and research priorities that would progress
73 the field. Here we present the results of a workshop hosted by the British Ecological Society’s
74 Microbial Ecology Special Interest Group in June 2016, which used a discussion and voting-based
75 system to identify 50 research questions of importance to the field of microbial ecology. Similar
76 exercises identifying important research questions have been conducted in conservation (Sutherland
77 *et al.*, 2009, Dicks *et al.* 2012), pure ecology (Sutherland *et al.*, 2013a), marine biodiversity (Parsons
78 *et al.*, 2014), sustainability (Dicks *et al.*, 2013; Jones *et al.* 2014), and non-ecological subjects
79 including UK poverty (Sutherland *et al.*, 2013b). These papers have been widely accessed and are
80 directly applicable to the development of policy, as highlighted by Jones *et al.* (2014).

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82

83 **Methods**

84 *Participants*

85 The methods used here were based broadly on those presented in Sutherland *et al.* (2011). A one-day
86 workshop was held by the British Ecological Society’s Microbial Ecology Special Interest Group at the
87 University of Salford (UK) in June 2016. Invitations to attend the meeting were distributed via the

British Ecological Society's membership mailing list and through social media (Twitter and Facebook).
In total, 34 participants from 20 institutions attended and contributed to the development of the 50 questions listed below, with the majority listed as authors on this paper.

91

92 Questions

93 Prior to the workshop, attendees were asked to submit questions via an online form that they thought
94 most closely met the following brief:

95 "We are aiming to identify 50 questions that, if answered, will make a considerable
96 difference to the use of microbial ecology by practitioners and policy makers, or to
97 the fundamentals of the field of microbial ecology. These should be questions that
98 are unanswered, could be answered, and could be tackled by a research
99 programme. This is expected to set the agenda for future research in the field of
100 microbial ecology."

101

102 A total of 244 questions were submitted by attendees (see Supplementary Information), and assigned
103 (by R.E. Antwis and S.M. Griffiths) to the following ~~eight~~ themes;

- 104 1) *Host-Microbiome Interactions*;
- 105 2) *Health and Infectious Diseases*;
- 106 3) ~~*Food Security and Human Health*~~ *and Food Security*;
- 107 4) *Microbial Ecology in a Changing World*;
- 108 5) *Environmental Processes*;
- 109 6) *Functional Diversity*;
- 110 7) *Evolutionary Processes*;
- 111 ~~8) *Methods in Microbial Ecology*.~~

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113 An additional ~~ninth~~ eighth theme named '*Society and Policy*' was created to capture a number of

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6 114 questions that were generally applicable across the biological sciences, as well as a number of
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8 115 questions specific to the field of microbial ecology which could not necessarily be addressed through
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10 116 laboratory based microbial ecology research, *per se*.

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14 118 *Question selection process*

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16 119 Prior to the workshop, participants were asked to identify the top ~20% of questions in each theme
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18 120 that most closely aligned with the brief (selection of 5-11 questions from a total of 26-57 questions per
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20 121 theme via online form; Supplementary Information). Participants were asked to consider all questions
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22 122 within a theme and to select questions based on the theme's context and the brief for the workshop.
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24 123 Some questions were included in more than one theme to encourage discussion and to increase the
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26 124 likelihood that pertinent questions remained in the selection process. Questions were then ranked
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28 125 according to the number of online votes they received, and this formed the material for the workshop.

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30 126 Three sets of parallel sessions were run at the workshop, with participants free to select which
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32 127 theme sessions they attended. Questions were discussed in order of lowest ranking to highest, with
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34 128 duplicates removed and questions reworded as necessary. For each theme, a final set of 'gold' (~15%
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36 129 of questions, total of 47 questions across all themes) and 'silver' questions (~10% of questions, total of
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38 130 29 questions) were identified. Where necessary, a show of hands was used to ensure the democratic
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40 131 process was upheld.

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42 132 A final plenary session was held in which all gold and silver questions were discussed. For
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44 133 gold questions, duplicates among categories were removed and questions reworded to reflect the
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46 134 discussion in the room, resulting in 43 gold questions. A similar process was then completed for silver
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48 135 questions, and a show of hands used to vote for seven questions that could be elevated to gold status
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50 136 to form the final set of 50 questions ~~across the eight themes~~.

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54 138 *Limitations*

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56 139 All but four participants were from British universities, although there were representatives from a
57
58 140 range of nationalities and research areas. The manner in which this paper was developed (*i.e.* through
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60 141 a physical workshop and via the British Ecological Society) means that, without a substantial travel

budget, a bias towards UK institutions was inevitable. However, many participants have worked on, or currently collaborate in, research projects on non-UK ecosystems and species, and therefore the questions proposed are drawn from considerable knowledge and experience of the field internationally. Additionally, although most individuals were from academic institutions, many individuals had previous or on-going collaborations with industrial partners and governmental/non-governmental organisations.

Results

The following 50 questions are presented by theme, and are not ordered according to relevance or importance. Due to the nature of the process, some questions may appear similar across themes, but within the context of each theme can take on a different meaning. Some questions may relate to research areas that are already somewhat active, and these serve to highlight the importance of and encourage further work in these areas. Some of these questions apply across multiple biomes and ecosystems, and can be considered in the context of multiple host organisms and across varying temporal and spatial scales.

Host-Microbiome Interactions

Host-microbiome interactions determine many host life history traits such as behaviour, reproduction, physiological processes, and disease susceptibility (Archie and Theis, 2011; Willing *et al.*, 2011; Koch & Schmidt-Hempel, 2011; Daskin & Alford, 2012; King *et al.*, 2016). The 'hologenome theory' suggests that the microbiome be considered an integral part of the host system, with the evolution of an individual's own genetic material and that of the associated microbiota intrinsically linked (Zilber-Rosenberg & Rosenberg, 2008; Daskin & Alford, 2012). Increasingly, we are discovering that host-microbiome interactions produce complex and dynamic communities that fluctuate in compositional abundance influenced by correlated with factors as diverse as host genotype, developmental stage, diet, and temporal changes, among others (e.g. Spor *et al.*, 2011). Even in otherwise well studied organisms, very little is known about the consequences of microbiome variation for host processes, particularly across different spatial and temporal scales. Considerations of host microbiomes are also likely important for global issues, such as the efficacy of conservation efforts including species

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7 171 reintroduction programmes (reviewed in Redford *et al.*, 2012; McFall-Ngai, 2015). Additionally,
8 172 interactions between native and non-native species are ~~affected by~~correlated with transmission of
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10 173 microbiota, often determined by relatedness or diet type (Ley *et al.*, 2008), and the microbiome plays a
11 174 key role in the control and competence of insect crop pests and vectors of disease (reviewed in Weiss
12
13 175 & Aksoy, 2011). The following questions aim to address the shortfall in our understanding of the
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15 176 interactions between microbiomes and their human and non-human hosts.

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21 179 1.4. What are the primary mechanisms within a host that mediate microbe-microbe and host-microbe
22 180 interactions?

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24 181 2. What are the relative contributions of host-associated and environmental factors in determining host
25 182 microbial community composition?

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26 183 3.2. How do microbial communities function to affect the phenotype of the host?

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28 184 4.3. Can compositional or evolutionary changes in microbiomes help hosts adapt to environmental
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30 185 change within the lifetime of the host?

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32 186 5.4. What is the role of the microbiota in host speciation processes?

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34 187 6.5. How can the associated microbiota be effectively included in risk assessments of Invasive Non-
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36 188 Native Species?

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38 189 7.6. How does the microbiome of captive ~~and head-started~~ animals affect the success of reintroduction
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40 190 programmes?

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42 191 8. How can a 'systems biology' approach improve our understanding of host-microbe interactions?

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49 194 **Health and Infectious Diseases**

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51 195 The last 50 years have seen the emergence of several hypervirulent wildlife pathogens in animals
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53 196 (e.g. Tasmanian devil face tumour disease, avian malaria, amphibian chytridiomycosis; reviewed in
54
55 197 Tompkins *et al.*, 2015) and plants (e.g. sudden oak and larch death, ash dieback; Pautasso *et al.*,

2015). Although the role of microorganisms as pathogens is well known, the importance of host-associated microbiomes in regulating disease susceptibility is becoming more apparent (Koch & Schmidt-Hempel, 2011; Daskin & Alford, 2012; King *et al.*, 2016). A major outstanding research goal is to understand how within-host interactions among microbes and invading pathogens may shape patterns of infection intensity and disease progression (see also *Evolutionary Processes*). Several studies have sought to determine how manipulation of host microbiomes may ameliorate the spread and impact of such diseases (e.g. Rebollar *et al.*, 2016).

While for many disease states the paradigm holds true that one microorganism causes one disease, polymicrobial infections are becoming more apparent through metagenomic and metatranscriptomic sequencing of disease-associated microbial communities (Gilbert *et al.*, 2016). Consequently, the “pathobiome” concept, where a disease state is influenced by complex interactions between commensal and pathogenic microorganisms, presents new challenges for applying Koch’s postulates to diseases arising from polymicrobial interactions (Vayssier-Taussat *et al.*, 2014), such as black band disease (BBD) in corals (Sato *et al.*, 2016) and olive knot disease (Buonaurio *et al.*, 2015).

In this ~~section-theme~~ we have identified research questions relating to the microbial ecology of infectious diseases and host health. Although much can be learnt from the comparatively high number of studies in the human and biomedical literature (e.g. using network approaches in epidemiology), the questions selected in this theme predominantly relate to non-human animals and plants, as humans are covered later (*‘Food Security and Human Health and’ Food Security*).

948. How can we better track the source and dispersal of particular microorganisms in real time?

107. Many microorganisms are unculturable, and many microbiome studies reveal that diseases are polymicrobial; how can we re-evaluate Koch’s postulates in this context?

118. Which factors trigger ‘covert’ infections to become ‘overt’, impacting host health?

129. At the population level, how is the burden and shedding intensity of intracellular microbes

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7 226 affected by co-infection by extracellular parasites?
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9 227 | 1349. What is the ecological relevance of the internalization of bacterial pathogens by protozoa in
10 228 terms of their survival and spread?
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12 229 | 144. How can network theory best be used to predict and manage infectious disease outbreaks in
13 230 animals and plants?
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16 231 | 152. Can microbiomes of wildlife (plants and animals) be used or manipulated to enhance health
17 232 and/or disease resistance?
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21 234 | Human Health and Human Health and Food Security and Human Health
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23 235 With the human population due to exceed eight billion by 2024, food security and human health are
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25 236 high on political and scientific agendas. ~~Though the remit for this section is relatively broad, the~~
26 237 ~~questions focus on two central themes: i) studying the human microbiome to improve the treatment of~~
27 238 ~~disease, including the development of personalized medicine and novel antibiotics; and ii)~~
28 239 ~~understanding how current antibiotic regimes and farming practices may negatively impact the~~
29 240 ~~diversity of the environmental microbiome and food production capacity.~~
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33 241 The human microbiome has been the focus of intense research efforts in recent years, (e.g. Walter &
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35 242 Ley, 2011; Spor *et al.*, 2011; Mueller *et al.*, 2012), because gut symbionts shape the immune
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37 243 response (Round *et al.*, 2009), and diversity fluctuates through chronic conditions and infectious
38 244 diseases including diabetes, obesity (Serino *et al.* 2016; Baothman *et al.*, 2016; Ridaura *et al.*, 2013),
39 245 asthma (Smits *et al.* 2016), and HIV (Lozupone *et al.*, 2013). Improving our understanding of the core
40 246 human microbiome and individual variation will underpin pharmomicrobiomics, enabling development
41 247 of novel therapeutic treatments and, ultimately, personalised medicine (e.g. Ubeda *et al.*, 2013).
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43 248 | ~~There was a strong interest in maintaining and enhancing the microbial populations of crop~~
44 249 ~~ecosystems, especially in light of antibiotic resistance (Ellouze *et al.*, 2014). As antibiotic resistance~~
45 250 ~~increases along with our concern about potential impact on both human and animal health, there is an~~
46 251 ~~increasing drive to find new forms of antibiotics.~~
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52 252 Antibiotic resistance resulting from selective pressures generated by the use and misuse of
53 253 antibiotics is a global threat to public health (Levy, 1997; Tam *et al.*, 2012). The volume of antibiotics

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used in agriculture now exceeds the amount used in human medicine in many countries (WHO, 2011). Antibiotics are still widely used in livestock for prophylaxis and growth promotion, often at sub-therapeutic concentrations, exacerbating resistance (Krishnasamy *et al.*, 2015). The impact of the leaching of antibiotics into the natural environment and subsequent impacts on natural microbial communities remains poorly characterised (Franklin *et al.*, 2016). Current practices of growing high-intensity monoculture crops have a negative impact on the microbial biodiversity of soils through a combination of tillage, subsequent erosion and chemical applications (Helgason *et al.*, 1998; Jacobsen and Hjelmsø, 2014; Zuber and Villamil, 2016), which imposes selection pressures on pathogenic microbes, fungal symbiotic partners and plant growth promoting bacteria (Chapparo *et al.*, 2012; Hartmann *et al.*, 2015). Thus, there iwas a strong interest inneed to maintaining and enhanceing the microbial populations of crop ecosystems, especially in light of antibiotic resistance (Ellouze *et al.*, 2014). As antibiotic resistance increases, along with our concern about potential impact on both human and animal health, there is an increasing drive to find new forms of antibiotics.

Though the remit for this section is relatively broad, the questions focus on two central themes: i) studying the human microbiome to improve the treatment of disease, including the development of personalized medicine and novel antibiotics; and ii) understanding how current antibiotic regimes and farming practices may negatively impact the diversity of the environmental microbiome and food production capacity. ~~This section examines ways in which we can harness microbial functions to improve overall human health through managing gut microbiota, and improve the soil and plant microbiome, thus increasing yields and associated biodiversity.~~

163. How can human microbiome studies improve personalised medicine?

174. What ecological principles can be applied in the search for new antibiotics and alternatives?

185. What are the main determinants of waterborne infection outbreaks, and what is the best strategy to control these in water distribution systems?

196. What are the consequences of antibiotic and pharmaceutical use in human medicine on microbial communities in freshwater and soil environments?

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7 282 | 20. To what extent are microbial species distributions influenced by climate, and what are the
8 283 | consequences for food security and human health?
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10 284 | 2147. How much microbial diversity in the soil has been lost through monoculture and what is the
11 | importance of this?
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14 286 | 2248. Intensive farming may involve high levels of agrochemicals and broad-spectrum antibiotic usage
15 287 | - what will be the long-term effects on microbial communities?
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17 288 | 2349. How best can we harness microbial communities to enhance food production?
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21 290 | **Microbial Ecology in a Changing World**
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23 291 | Global changes resulting from human activity impact almost every Earth-habitat on earth. It is
24 292 | imperative that we focus efforts on understanding the impacts of human activities such as climate
25 293 | change, urbanisation, agriculture, and industrial processes on microbial communities, ecosystem
26 294 | functioning equilibrium, and host health. Microbial populations have a tremendous capacity to adapt to
27 295 | changes in their abiotic environment, yet the functional implications of these transitions in microbial
28 296 | ecology are still poorly understood and characterised (Bissett *et al.*, 2013), and the role of microbes in
29 297 | mediating the response of larger organisms to change is equally understudied. Plant-associated
30 298 | microbial communities can alter the performance of subsequent generations of plants, and can
31 299 | themselves be subject to the concomitant effects of abiotic change (van der Putten *et al.*, 2013). Such
32 300 | plant-soil feedbacks can reduce yield and alter the community composition and invasibility of whole
33 301 | areas of grassland (van der Putten *et al.*, 2013). Global environmental changes (GECs) are complex
34
35 302 | and multifaceted. Human activities such as urbanisation, land-use change and introduction of invasive
36 303 | species have played a role in shifting global ecosystems via desertification, climate change and
37 304 | habitat degradation. Although such changes have been quantified in aquatic and terrestrial habitats
38 305 | (e.g. Haberl *et al.*, 2007; Halpern *et al.*, 2008), their effects on microbial communities and impacts on
39 306 | ecosystem function are often hindered by a lack of characterisation of communities, or limited
40 307 | understanding of microbial functional traits. Shifts in basic nutrients and gases such as CO₂, along
41 308 | with temperature fluctuations and water availability, greatly influence the distribution and behaviour of
42 309 | species (Tylianakis *et al.*, 2008). GECs can alter host fitness or ecosystem functioning (Shay *et al.*,
43 310 | 2015; Webster *et al.* 2016) and are likely to occur in combination. While there is a great deal of

research into the effects of each of these on microbial communities (Schimel *et al.*, 2007; Shurin *et al.*, 2012; Lloret *et al.*, 2014), literature considering the effect of multiple GECs is ~~more sparse~~^{sparser}, and these have complicated and often unpredictable consequences when combined (although see Hutchins *et al.*, 2009; Ryalls *et al.*, 2013). In this section, we consider how human activities directly and indirectly influence the microbial world. Where applicable, these questions can be considered across multiple biomes and ecosystems, with reference to resulting trophic cascades, in addition to the impacts on multiple biogeochemical processes. We also consider how microbes can be used as a tool for mitigation or bioremediation of human-induced environmental changes, and the ways in which microbes can be included in current evaluations of global change.

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240. How can we integrate microbial communities into models of global change?

254. Will ocean acidification, temperature increases and rising sea levels lead to changes in microbial diversity or function, and what will the cascading effects of this be?

262. How do human activities, such as oil and gas drilling, influence the sub-surface microbiome(s)?

273. How will increasing urbanisation affect environmental and host-associated microbial communities?

28. How resilient are different microbial functional groups to ecosystem disturbance?

294. Can we manipulate microbial succession in species-poor soils to encourage repopulation by flora and fauna?

330

Environmental Processes

Microbes play a fundamental role in environmental processes and ecosystem services, including nutrient cycling and organic matter decomposition (Chin *et al.* 2016; Creamer *et al.*, 2015; Weider *et al.*, 2013), bioremediation of contaminated habitats or waste systems (Haritash & Kaushik, 2009; Oller *et al.*, 2011), and influencing greenhouse gas emissions (Singh *et al.*, 2010; Bragazza *et al.*, 2013; Hu *et al.*, 2015). The ability to harness these processes has great potential for societal and environmental applications, particularly in extremophiles, which frequently reveal metabolic capabilities and evolutionary solutions not witnessed elsewhere in the microbial world (Coker *et al.* 2016). However, it

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is rarely possible to directly link the presence of a specific microbial taxon to a particular ecological process. Other methodological challenges include establishing the relative importance of biotic and abiotic factors in microbial ecosystem function, and determining the appropriate spatial and temporal scale necessary to discriminate links between microbiota and their ecological functions (Bissett *et al.*, 2013). Concurrently, a deeper understanding is required of human-induced impacts on the global microbiome through urbanisation, habitat degradation, climate change, and the introduction of invasive species, amongst others.

[3025](#). How do we successfully establish microbial communities used in bioremediation?

[3126](#). How important is the rare microbiome in ecosystem function, and how does this change with stochastic events?

[3227](#). To what extent is microbial community diversity and function resilient to short- and long-term perturbations?

[3328](#). What is the importance of spatial and temporal variation in microbial community structure and function to key environmental processes and geochemical cycles?

[3449](#). How can we accurately measure microbial biomass in a reproducible manner?

[3529](#). Which mechanisms do extremophiles use for survival and how can they be exploited?

Functional Diversity

Ecologists are increasingly turning their attention to classifying species based on their activity (function) within an ecosystem, rather than their genotype (Crowther *et al.*, 2014). This is particularly relevant for microbial ecology, in which species are hard to define, horizontal gene transfer is rife, and taxonomy is often blurred. Understanding how membership within complex and dynamic microbial communities relates to the function of that community is one of the key challenges facing microbial ecology (Widder *et al.*, 2016). This is true across a vast range of spatial scales, from microbial dyads to the gut of a *Drosophila* fly, to ancient trees and their associated ecosystems, right through to global

biogeochemical processes. There is an urgent need to understand how the genome ~~or~~ hologenome of a microbial community (and in some cases, its host) relates to metabolic capacities. Conversely, there is also a need to understand how ecosystems depend on a particular organism or group of organisms for any given process and function. This section describes the need to move from simply describing microbial diversity to understanding what these organisms are doing, how they are doing it, and what biotic and abiotic drivers are controlling their activity. Each question may derive a suite of different answers, depending on the group of organisms, the habitat and the process.

360. What are the mechanisms driving microbial community structure and function, and are these conserved across ecosystems?

37. What is the relative importance of stochastic vs. determinative processes in microbial community assembly?

384. How conserved are microbial functions across different spatial and temporal scales?

392. What is the relative importance of individual 'species' for the functioning of microbial communities?

4033. How much functional redundancy is there in microbial communities, and how does functional redundancy affect measures of diversity and niche overlap?

4134. How often are functional traits of microbes successfully conferred through horizontal gene transfer?

4242. What methods can we use to marry microbial diversity with function; how do we link transcriptomics, proteomics and metabolomics?

43. How do we move beyond correlation to develop predictive models that advance our understanding of microbial community function and dynamics?"

4450. How useful are synthetic communities for ~~testing~~ inferring theories about microbial community dynamics and function?

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10 395 **Evolutionary Processes**
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12 396 The role of microorganisms in determining evolutionary outcomes of hosts is being investigated in
13 397 increasing detail (McFall-Ngai *et al.*, 2013). Experimental evolution studies represent a powerful
14 398 means of quantifying host-microbe and microbe-microbe coevolution, and have highlighted the
15 399 extraordinary capacity of microbes to act as key mediators of host fitness (e.g. King *et al* 2016). Whilst
16 400 experimental coevolution studies provide a framework for linking dyadic interactions to community-
17 401 scale dynamics (Brockhurst & Koskella, 2013), evolutionary principles stemming from macro-ecology
18 402 are being applied to microbial communities of humans (Robinson *et al.*, 2010). However, fundamental
19 403 biological questions that are well-studied in macrobiology remain controversial for microbial ecology,
20 404 for example the species concept remains a source of debate (Freudenstein *et al.* 2016). The
21 405 operational taxonomic unit (OTU) has become the standard unit for identifying bacteria at the highest
22 406 taxonomic resolution possible, yet it is hard to clearly define where taxonomic boundaries lie between
23 407 two bacteria, and what an OTU really represents in biological terms. This is especially problematic in
24 408 the context of horizontal gene transfer, which is commonly observed in bacteria and has turned our
25 409 understanding of evolutionary processes upside down. This section relates to how general ecological
26 410 principles influence microbial evolution and *vice versa*, what this means for global biodiversity, and
27 411 whether evolutionary principles can be utilised for anthropogenic gain.
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32 413 [4535](#). How can a bacterial 'species' be defined?
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34 414 [4636](#). To what extent is faunal and floral biodiversity influenced by microbial communities?
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36 415 [4737](#). To what extent do microbial communities have an equivalent to keystone 'species'?
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38 416 [4838](#). Does the structure of microbial communities conform to the same ecological rules/principles as
39 417 in other types of communities?
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41 418 [439](#). How do fundamental shifts in environmental conditions impact the trajectory of microbial
42 419 evolution?
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44 420 [5040](#). What are the relative selective forces favouring microbial genome expansion or reduction?
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421 41. Can experimental evolution predict how antimicrobial resistance evolves *in vivo*?

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423 ***Methods in Microbial Ecology***

424 Methods for assessing microbial diversity and community function have rapidly advanced in recent
425 years, with a major shift from culture dependent to molecular based techniques that produce vast
426 quantities of data (Rohwer, 2007; Bitten *et al.*, 2015). Advances in technologies for the analysis of
427 (meta)genomes, (meta)transcriptomes, (meta)proteomes and metabolomes, with associated
428 computational biology tools, have revolutionised our understanding of microbial diversity and function,
429 with multi-'omics' approaches providing unprecedented opportunities to assess genomic potential,
430 gene regulation, expression and functionality *in situ*. There are still many challenges relating to
431 methods for analysing and describing microbiomes, elucidating the roles these microorganisms play
432 both individually and as a community, and how this relates to wider organismal function and
433 environmental processes (Robinson *et al.*, 2010). Amplicon studies also raise the problem of how to
434 link taxonomic identity to functional ability. The vast datasets produced by the 'omics' technologies
435 present unique statistical challenges, requiring new analytical techniques and approaches (Weiss *et al.*, 2016ab). Simultaneously, high-throughput culture based methods are being re-invented for
436 applications such as antibiotic discovery (Ling *et al.*, 2015; Oberhardt *et al.*, 2015). There is no one-
437 size fits all method for a given type of study, but it is desirable to have a suite of robust methods that
438 can be applied in a comparable manner to achieve results with a high level of confidence (Bustin *et al.*, 2009). As contemporary technological advancements improve the accessibility, throughput,
439 resolution and cost of microbiome analysis, this section explores some of the new challenges that
440 arise due to rapid advancements within the field, and other research questions that can be addressed.

443

444 42. What methods can we use to marry microbial diversity with function; how do we link
445 transcriptomics, proteomics and metabolomics?

446 43. How can we handle the unassigned sequences that dominate metagenome datasets?

447 44. How can we develop a standardized best practice method for analysing sequence data to estimate
448 relative abundance?

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7 449 ~~45. What is the most appropriate taxonomic level at which to compare microbial community~~
8 450 ~~compositions?~~
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10 451 ~~46. How can systems approaches improve our understanding of host-microbe interactions?~~
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12 452 ~~47. How do we move beyond correlations to determine cause and effect in microbial~~
13 453 ~~communities/ecosystems?~~
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16 454 ~~48. How can we better track the source and dispersal of particular microorganisms in real time?~~
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18 455 ~~49. How can we accurately measure microbial biomass in a reproducible manner?~~
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20 456 ~~50. How useful are synthetic communities for inferring theories about microbial community dynamics?~~
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22 457
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24 458 **Society and Policy**
25
26 459 We need to find ways to apply fundamental biological research to the benefit of society and policy. For
27 460 example, collaboration with social scientists is crucial when investigating public understanding of
28 461 microbial ecology, as well as using citizen science approaches to tackle microbial ecology research
29 462 questions. Many questions relating to this area were discussed at the workshop, and here we present
30 463 four additional questions that were developed at the meeting that relate to societal and policy-based
31 464 aspects of microbial ecology.
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- How can we best address supply and demand of information about microbial ecology between

39 467 researchers, clinicians, policy makers and practitioners?
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- How can we best use social and traditional mass media for early identification of emerging

43 469 threats to animal and plant health?
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- How can we develop an open access data repository or integrate existing databases to create

46 471 a centralised and standardised method for data and methods sharing in microbial ecology?
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- How can we replace fear-based regulation with risk-based regulation, specifically with regard

50 473 to the use of microbes in bioremediation and bioaugmentation?
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475 **Discussion**

476 Here we present 50 important research questions across eight-a number of themes relating to the field
477 of microbial ecology. Although there are many other research issues worthy of investigation, it is
478 intended that these questions will be used to inform and direct future research programmes and
479 agendas, particularly in areas where microbial ecology has not previously been considered or applied.
480 In many cases, these questions are deliberately broad to allow researchers to adapt them to their own
481 areas of interest, for example across different systems, or to varying spatial scales. Across many
482 questions there was strong recognition of the vast metabolic capabilities of microorganisms and
483 microbial communities, and the need to harness this power to improve human and animal health and
484 wellbeing. Some themes addressed various existing mechanisms for exploiting microbial processes,
485 namely bioremediation, soil improvement, water treatment and probiotic suppression of pathogen
486 resistance. As these are already active areas of research, the questions posed here are structured to
487 provide a framework by which these efforts can be directed in the future.

488 A predominant theme that emerged was the need to integrate knowledge between different
489 research areas, for example the application of information from human microbiome studies to the
490 study of other non-model host organisms, and the potential to apply macro-ecological frameworks to
491 micro-ecological concepts. Many fundamental biological questions that are well-studied in classical
492 ecology remain controversial for microbial ecology, and the species concept (Freudenstein *et al.*
493 2016), taxonomy, and how the OTU should be defined for microorganisms, generated multiple
494 questions (e.g. see '*Evolutionary Processes*' theme). Classical community ecology concepts should
495 not be overlooked when considering microbial dynamics (Rynkiewicz *et al.*, 2015) and, conversely,
496 microbial communities may prove useful models for general ecology due to their short generation
497 times, reproducibility, and ease of use in the laboratory environment (Brockhurst & Koskella, 2013;
498 Libberton *et al.*, 2015; King *et al.*, 2016). There have been a number of calls for the medical profession
499 to look to ecological and evolutionary tools when seeking to understand epidemiology (Johnson *et al.*,
500 2015), investigating novel antibacterial agents (Vale *et al.*, 2016), and considering multi-host, multi-
501 agent disease systems (Buhnerkempe *et al.*, 2015).

502 The '*Host-Microbiome Interactions*' theme considered the need to understand factors
503 influencing microbiome composition, which in turn have consequences for a myriad of host traits,
504 including disease susceptibility and host evolution (Chisholm *et al.*, 2006; Archie & Theis, 2011; Spor

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7 505 *et al.*, 2011; Cho & Blaser, 2012; McFall-Ngai *et al.*, 2013; McFall-Ngai, 2015; Zilber-Rosenberg &
8 506 Rosenberg, 2008). As this theme considered microbiota from the perspective of the host, there was
9
10 507 some overlap with the '*Health and Infectious Diseases*' and '*Evolutionary Processes*' themes.
11 508 Probiotics were discussed as a viable and promising alternative to current strategies in a number of
12 contexts in these themes, not only to improve individual health, but also to decrease disease
13 509 susceptibility of humans and other animals, to enhance nutritional quality of food, and to mitigate the
14 510 negative impacts of antibiotic use across humans, livestock, aquaculture and agriculture (Martín *et al.*,
15 511 2013; Newaj-Fyzul *et al.*, 2014; Smith, 2014; Fox, 2015). Developing personalized probiotic-based
16 512 therapies requires complementary diversity and functional-based studies in order to elucidate the
17 513 specific roles of microbiota in health and disease, and thus how microbial communities can be
18 514 manipulated.
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23 516 Likewise, qQuestions considered in both the '*Functional Diversity*' theme and the
24 517 '*Environmental Processes*' theme raised a common need to understand changes in microbial
25 518 community structure and function across spatial and temporal scales (Carmona *et al.*, 2016).
26 519 Establishing appropriate spatial scales for studying microbial processes is an outstanding challenge:
27 520 micro-organisms can orchestrate ecosystem functioning across whole biomes (Sheffer *et al.*, 2015),
28 521 yet fungi exhibit low mobility on tree barks (Koufopanou *et al.* 2006, Robinson *et al.*, 2016), and an air
29 522 void in soil can be an insuperable barrier for a bacterium. Similarly, drawing meaningful conclusions
30 523 about microbial processes requires understanding of their temporal variability; for ~~exampleexample,~~
31 524 diurnal influences (Shurpali *et al.*, 2016), or lags behind changes in ecosystem drivers (Allison and
32 525 Martiny, 2008). ~~These concerns were ultimately addressed in a single question (question 28).~~
33
34 526 ~~Questions identified in this paper highlighted the need for knowledge that~~
35 527 ~~informs antibiotic use and production, and to optimise the sustainability of food~~
36 528 ~~production through improved soil fertility. There was a strong interest in maintaining~~
37 529 ~~and enhancing the microbial populations of crop ecosystems, especially in light of~~
38 530 ~~antibiotic resistance (Elhouze *et al.*, 2014). As antibiotic resistance increases along with~~
39 531 ~~our concern about potential impact on both human and animal health, there is an~~
40 532 ~~increasing drive to find new forms of antibiotics~~
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Probiotics were discussed as a viable and promising alternative (Martin et al., 2013; Newaj-Fyzul et al., 2014; Smith, 2014; Fox, 2015), not only to improve individual health, but also to decrease disease susceptibility, enhance nutritional quality of food, and to mitigate the negative impacts of antibiotic use across humans, livestock, aquaculture and agriculture (Martin et al., 2013; Newaj-Fyzul et al., 2014; Smith, 2014; Fox, 2015). Developing personalized probiotic-based therapies requires complementary diversity and functional-based studies in order to elucidate the specific roles of microbiota in health and disease, and thus how microbial communities can be manipulated.

Global changes resulting from human activity impact almost every Earth habitat. It is imperative that we focus efforts on understanding the impacts of human activities such as climate change, urbanisation, agriculture, and industrial processes on microbial communities, ecosystem functioning equilibrium, and host health. Microbial populations have a tremendous capacity to adapt to changes in their abiotic environment, yet the functional implications of these transitions in microbial ecology are still poorly understood and characterised (Bissett et al., 2013), and the role of microbes in mediating the response of larger organisms to change is equally understudied. Plant-associated microbial communities can alter the performance of subsequent generations of plants, and can themselves be subject to the concomitant effects of abiotic change (van der Putten et al., 2013). Such plant-soil feedbacks can reduce yield and alter the community composition and invasibility of whole areas of grassland (van der Putten et al., 2013). Discussions resulting from the 'Functional Diversity' theme (questions 30-34) addressed the need to move from simply describing microbial diversity to understanding what organisms are doing, how they are doing it, and which biotic and abiotic drivers control this activity. Each of these questions will likely derive a suite of different answers, depending on the group of organisms, the habitat and the process; the questions presented in this section were therefore some of the broadest discussed.

Large-scale assessments of ecosystem services and degradation acknowledge the paucity of data on microbial impacts, presumably because there are no convincing large-scale messages that can be derived at this stage (Norris et al., 2011). Microbial diversity is therefore rarely considered when estimates of biodiversity are required for policy or management decisions. Microbial diversity, abundance and influence on the biodegradation of important naturally-produced atmospheric hydrocarbons such as isoprene, have recently been studied to determine which micro-organisms are important in the sink of this global climate altering gas (Dumont & Murrell, 2015; El Khawand et al.

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~~2016). Another key greenhouse gas that needs further study is methane, the flux of which is regulated by methanotrophic bacteria and methanogenic Archaea, and can substantially alter the carbon balance of a system and have grave consequences for global climate change (e.g. Schuur *et al.* 2015; James *et al.* 2016). Solving these types of questions will help us to understand the impact of human activities on microbial ecology, and to find new solutions to the environmental and health problems we are currently facing and will continue to face in the future.~~

A subject common to a number of themes was the role of individual species *versus* consortia in ~~ecosystem community~~ functioning. The question of defining bacterial species is a contentious topic, and the issue remains whether some microbial taxa act as keystones in ecosystem functions. Many microbial surveys carry the implicit assumption that the most abundant taxa are also the most important, yet rare species can be hugely significant if they are highly active and/or monopolise a particular process (Lynch and Neufeld, 2015). The collective metabolic capabilities of micro-organisms have great potential for *in situ* applications such as bioremediation, particularly when used in multi-species consortia (Mikesková *et al.*, 2012). Successful bioremediation and environmental management requires the introduction of new assemblages ~~wholesale~~ into an established community, or stimulation of key members of the community *in situ* (Rillig *et al.*, 2015). In turn, predicting the successful establishment of deliberately introduced organisms depends on an understanding of the principles underlying microbial community formation and structure (Rillig *et al.*, 2015). Despite these challenges, functional diversity modelling has successfully been applied to the ecological restoration of some plant communities (Laughlin, 2014). Closely linked to this is the issue of functional redundancy, and to what extent it is possible to lose species without affecting ecosystem functions. Already there is evidence that microbial communities may be less functionally redundant than macro-organism communities (Delgado-Baquerizo *et al.*, 2016). This issue ties into fundamental ecological concepts, such as niche theory (Carmona *et al.*, 2016); if multiple organisms are carrying out the same process, apparently interchangeably, how do they avoid competitively excluding one another? The concept of keystone species has been shown to be applicable to microbes (Neufeld *et al.*, 2008; Pester *et al.*, 2010; Ze *et al.*, 2012; Yu *et al.*, 2016), yet further work is needed to characterise the extent to which keystone functions occur in different environments and whether these can be consistently identified (Anderson, 2003; Pester *et al.*, 2010).

~~Recent major technological and analytical advancements have made previously inaccessible~~

593 taxa and ecosystems amenable to study. Despite the opportunities afforded by big data however,
594 there are huge challenges when handling next generation sequencing data, both in the size of the
595 datasets and the spurious inter-correlation (compositionality) inherent to the sequencing process
596 (Weiss *et al.*, 2016a). There is community wide recognition that current methods of analysis are not
597 adequate to deal with the big data produced by next-generation sequencing, and a number of groups
598 have already attempted to establish standardised analysis methods (e.g. amplicon sequencing of
599 bacterial and fungal communities (Thomas *et al.*, 2012; Smith & Peay, 2014), and bioinformatics of
600 targeted and shotgun metagenomics (Bokulich *et al.*, 2013; McMurdie & Holmes, 2014; Oulas *et al.*,
601 2015; Randle-Boggis *et al.*, 2016). These methods now require validation under different contexts to
602 keep analyses with similar aims and methods comparable (Weiss *et al.*, 2016a,b). This is no easy task
603 given the plethora of decisions made throughout research design, from sample collection and storage
604 to lab work and data analysis (Callahan *et al.*, 2016), each of which introduce complexity to a study's
605 approach.

606 The need for open access databases and repositories, both in the context of data sharing as
607 well as for methods and protocols, was reflected in the questions shortlisted for the 'Society and
608 Policy' theme. Discussions included the benefits of forming collaborative and open research
609 communities, and the need to ensure the legacy of academic research through improving regulation
610 and policy and engagement with the public. Fear-based regulation of research, grounded in alarmist or
611 populist campaigns, as opposed to risk-based regulation built upon evidence, was identified as a
612 possible obstacle to progress, which could be addressed through greater interaction between
613 microbial ecologists and the public at both governmental and grass roots levels. Large scale
614 assessments of ecosystem services and degradation acknowledge the paucity of data on microbial
615 impacts, presumably because there are no convincing large-scale messages that can be derived at
616 this stage (Norris *et al.*, 2011). Microbial diversity is therefore rarely considered when estimates of
617 biodiversity are required for policy or management decisions. That said, the increasing recognition of
618 the fundamental impact of the microbial world on the functioning of larger-scale processes has made
619 the deliberate manipulation of the microbial world a controversial subject, which was reflected in the
620 number of draft questions submitted related to bioremediation and bioaugmentation (see
621 Supplementary Information). Collaboration with social scientists was identified as crucial in gauging
622 the public understanding of microbial ecology, and citizen science approaches were considered as

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6 623 tools to tackle key microbial ecology research questions. ▲
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9 624 The 50 questions identified here cover a broad range of topics, but some over-arching themes
10 625 recur across multiple questions, including a recognition that microbes play an important role in a
11 626 variety of different processes and systems, which may be harnessed to solve real-world problems.
12
13 627 There were some similarities between the questions identified here and those identified by previous
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15 628 workshops of a similar nature. For example, questions relating to soil health and biodiversity (Dicks *et*
16 629 *al.* 2013), a requirement for developing a theoretical understanding of micro- and macro- ecological
17 630 concepts (Prosser *et al.* 2007, Sutherland *et al.* 2013a) and disease dynamics (Prosser *et al.* 2007,
18 631 Sutherland *et al.* 2013a) have a degree of commonality with this list. This indicates that the ecological
19 632 theory underpinning many research questions transcends scientific disciplines, and that there is still
20
21 633 much work to be done at both theoretical and applied levels. Within these 50 questions, we have tried
22
23 634 to provide a focus for researchers addressing scientific questions from a microbial perspective,
24
25 635 regardless of their background. It is expected that these questions will facilitate interesting discussion
26
27 636 and new, exciting, interdisciplinary research. The list is by no means exhaustive, and we recognise
28 637 that the questions presented here are relatively community-centric, primarily due to the recent
29 638 expansion in methodological approaches that have improved our understanding of microbial
30 639 community diversity and function. That said, other areas of microbial ecology should not be ignored or
31 640 forgotten. and gGiven the rapidly evolving field of microbial ecology, it is expected that future
32
33 641 workshops with a wide draw will be held to ensure that the identification of research priorities and
34
35 642 areas of interest is a continuing process.
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42 **Funding**
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Are all families of bacteria capable of acquiring pathogenicity or are there barriers to the exchange of cer

Are all functional traits horizontally transmissible?

Are comparisons of microbial community composition at phylum level overused and uninformative?

Are faunal and floral biodiversity driven by microbial communities?

Are outdated species and subspecies definitions impeding our understanding of microbial ecosystems?

Are prosperous and diverse microbial communities that can auto-regulate less harmful, or risk-prone, tha

Are social scientists and economists going to be present in the panels on animal and plant health of the E

Are species just a handful of relatively stable lineages within gene pools in which horizontal gene transfer

Are studies which consider microbes by genus adequate in light of observed interspecies variation?

Are synthetic communities useful in inferring theories about microbial community dynamics?

Are the genes related with metabolic function vertically or horizontally inherited

Are there any unexplored 'microbial frontiers'?

Are there difference in microbiomes of heather under different management regimes?

Are there differences between skin microbiome of rural compared to urban amphibians?

Are there species or just highly integrated microbial communities?

As climate change continues to impact the global ecology, can monitoring microbial communities give an

As climate change effects soils including salinity, water levels and temperature, will this impact on food p

As extreme environments are being perceived as offering the best option for novel antimicrobials what h

As fracking looks increasingly likely to happen in the UK, what will be the effect on the surrounding micro

As it is may already have gone past the tipping point for climate change, can evolution be monitored in ei

At what spatial scale do we need to study microbial communities to answer applied or globally important

Can a better understanding of microbial ecology give us clues on how complex larger ecosystems functioi

Can bacteriophages be used to eliminate certain bacteria in an environmental sample?

Can bioinoculation based bioremediation techniques be deployed more successfully as a result of omics

Can endohyphal bacteria positively impact the environment through their host?

Can host community assemblages be used to predict parasite (micro and macro) community composition

Can media monitoring be used for early identification of new emerging threats to animal and plant health

Can metagenome analysis completely replace phylogenetic markers to describe diversity in microbiomes

Can micro-organisms be cultivated directly in soils using greenhouses?

Can microbes 'prime' each other to degrade organic matter?

Can microbes go extinct?

Can microbial communities ever be considered stable or is stability an artefact of the spatial scale by whi

Can microbial ecology provide an alternative to antibiotics?

Can microbial ecology tell us anything about non-microbial ecology?

Can probiotic microbiota mitigate water-stress induced plant disease?

Can regional outbreaks of exotic tree diseases become opportunities for nature conservation?

Can the gut mirobione be manipulated to enhance health?

Can understanding the relationship between ash die back disease and microbial community be used in sp

Can we come up with a standardized method for estimating relative abundance of high-throughput data?

Can we distinguish individual from interactive microbial effects? e.g. microbes that "turn on" (or off) path

Can we effectively synthesize microbial communities specialized in decomposing waste and recycling for

Can we genetically engineer endohyphal bacteria that are known to be the cause of plant disease to exer

Can we integrate our understanding of different microbiomes?

Can we manipulate migratory bacteria in soil in a way that it's useful for applications other than bioremediation?

Can we predict the functioning of communities from data on individual species within it (e.g. metabolic capabilities)?

Can we quantify the role of microbes in the major global geochemical cycles (e.g. carbon, nitrogen, methane)?

Can we study ancient microbial communities, and use that information to predict microbial community evolution?

Do different functional clades have differing critical thresholds with regards to ecosystem disturbance?

Do ecological interactions have role in bacterial plasticity?

Do metagenomics and amplicon sequencing provide useful information about the actual functionality of microbial communities?

Do microbial communities have keystone species or an equivalent e.g. a keystone functional clade?

Do microbial ecologists know enough microbiology?

Do specific global ecosystems warrant particular focus and further study?

Do the tenets of prokaryotic microbial ecology hold true for eukaryotic species and genera?

Do we need models in microbial ecology?

Do we see similar biogeographical patterns for microbes as for 'macrobes'? If not, why not?

Does Applied Microbial Ecology exist?

Does microbial ecology require more specialist lab equipment?

Does the biodiversity of rhizosphere microorganisms change according to the type of root, depth of the root, etc?

Does the microbiota affect host behaviour?

Does the presence of introduced fish in high mountain lakes impact on water quality and microbial communities?

For a given microbial process, what spatial scale(s) does it operate at?

Fracking releases the groundwater and may cause increase in pollutants, how will this effect groundwater quality?

Fungi can be found in various extreme environments. Why haven't we found many deep-sea fungi that are extremophiles?

Gaia theory - is there more to be explained by microbial ecology?

How accurate are our measurements and understanding of in situ processes or are we extrapolating from lab results?

How best can we harness insect microbial pathogens for biological control of crop pests?

How best do we validate models of microbiomes through experiments and collecting samples from the field?

How can a bacterial 'species' be defined?

How can amplicon data be produced and analysed in a robust and comparable way?

How can deep-sea fungi adapt to the lack of light and autotrophic organisms?

How can microbial ecology inform conservation studies?

How can microbial ecology best support the advancement of agriculture?

How can microbiome studies improve personal medicine?

How can systems approaches improve our understanding of host-microbe interactions?

How can the economic and social relevance of microbial ecology be reinforced with funding and decision making?

How can we account for variations in genome length when measuring variations in abundance and diversity?

How can we accurately measure soil microbial biomass in a reproducible manner?

How can we advance our screening methods to map microbes from "extreme" environments?

How can we apply modelling techniques to analyse the risks of ecological and agricultural probiotics?

How can we assess the role of the unculturable microbiome in the ecology of real habitats?

How can we better measure dispersal capacities of microbes?

How can we better track particular microbes in communities?

How can we compare the roles of decomposition between terrestrial and aquatic fungi?

How can we culture communities of environmental microbes in situ?

How can we develop suitable software programmes, tools, statistical approaches and databases to analyse microbial ecology data?

1 How can we examine ecological processes (e.g. N mineralisation) on a scale relevant to microbes?
2 How can we get young people interested in invisible, boring microbes?
3 How can we identify microbial species in the environment in real-time?
4 How can we improve the proportion of microbial diversity that is isolated and held in pure culture?
5 How can we interpret Koch's postulates in relation to polymicrobial infections as revealed by microbiome
6 How can we make microbial ecology relevant to policy makers?
7 How can we measure the hidden diversity? Overcoming arbitrary cut off values in next-generation sequencing
8 How can we prove that microbes have ecosystem-scale impacts?
9 How can we relate large-scale taxonomic information to fine-scale function?
10 How can we solve the most pressing career issues affecting early stage researchers in microbial ecology?
11 How can we stop pathogens from forming biofilms?
12 How certain is genetic decay in a symbiont
13 How cosmopolitan are microorganisms?
14 How diverse is a 'community'?
15 How do differences in microbial communities in human and animal microbiomes relate to different diseases
16 How do gut bacterial communities interact with viral infections? Can we classify communities as "neutral"
17 How do microbial communities interact to effect the phenotype of the host?
18 How do plant endophytes enter, become active in, and influence their hosts?
19 How do protists influence fungi in soil?
20 How do skin microbiota and UV interact in amphibians, especially at high altitude?
21 How do soil bacteria, viruses and archaea interact?
22 How do viruses influence microbial ecology?
23 How do we establish effective sample sizes for studies of poorly characterised microorganisms?
24 How do we sample environmental variables at an appropriate scale that are proximate to microbial communities
25 How does individual microbiota affect others at a community level
26 How does the environment select?
27 How does the microbiome influence health?
28 How important is the "rare" microbiome in ecosystem function?
29 How important is the microbiota in mediating adaptation that results in species invasions?
30 How is best to study the changing resource environment of microbial communities?
31 How is climate change going to affect the microbial communities in the drinking water distribution system
32 How much functional redundancy is there in microbes relative to higher taxa?
33 How much functional redundancy is there in microbial communities, and how does that interact with diversity
34 How much functional redundancy is there in the host microbiome?
35 How much intra- vs inter-specific trait variation is there?
36 How much microbial diversity in the soil has been lost through monoculture and what is the importance of
37 How problematic is PCR amplification bias?
38 How similar is the rhizosphere biodiversity of microbes from the same species of tree located in different
39 How stable are microbial communities, and how can we assess their stability, particularly in changing environments
40 How to foster interdisciplinary approaches in and around microbial ecology?
41 How to solve the leaky pipeline of female microbial ecologists in academia?
42 How to solve the peer reviewer crisis in microbial ecology?
43 How well do current species distribution models developed with microbial systems predict the distribution of
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How will different temperature and humidity regimes reflecting likely climate change scenarios affect lea
How will predicted climate changes influence the free-living stages of terrestrial and aquatic helminths?
Intensive farming may involve high levels of broad spectrum antibiotic usage. This in turn will end up in t
Is Alan McCarthy the oldest microbial ecologist on the planet?
Is everything everywhere?
Is it necessary/important to document microbial diversity? Should it be done at the genus/species level?
Is it still relevant to dig for antibiotics?
Is it syntrophy the main metabolic mechanism sustaining microbial cooperation
Is it time to stop cataloguing bacterial community compositions in different habitats and put a bit more e
Is microbial abundance and/or diversity driving ecosystem functioning?
Is microbial ecology restricted by the red tape surrounding releasing microbes into the environment?
Is the carbon source used in general/selective media the limiting factor for some un-culturable micro-org
Is the growth in microbial ecology publication sustainable?
Is there a relationship between microbial community and ecosystem functioning, and is it observed across
Is there a way to overcome big data?
Is there any point in doing comparative metagenomics?
Is there going to be an improvement in the file-drawer problem (i.e. the tendency of positive results to be
Is there such thing as a microbial pathogen?
Is virus burden and shedding intensity in mammals amplified when co-infected by helminths?
Many hands make light work? What is the role of functional redundancy in ecosystem processes?
mechanisms extremophiles utilise for survival and potential uses elsewhere
No biome is an island. As interest in this area increases, how do microbiomes interact outside the microb
Not Waving but Drowning; how much evidence do we need to fully interpret omics data?
One size fits all? Is there a relationship between microbial and "macrobial" ecology?
Pathogens get a lot of mainstream attention. Should researchers do more to promote positive microbial i
plant host interactions, symbiotic relationships
Rapid detection and identification of microbes
Sequencing data has increased significantly in the last 15 years, will bioinformatics be the future of our st
Should new species descriptions based entirely on sequences be allowed?
Should researchers place greater emphasis on evaluating microbe functional traits (applied aspects), and
Should we be concerned about the extinction of microbial species?
Should we couple microbial ecology with Invasive Non-Native Species (INNS) risk assessments?
Society and policy makers; do they value microbial ecosystem services?
Soil microbial communities and the role they play
Soil microbial communities and the role they play
Soil profiling has been done for many years, can we estimate the type of organisms in a soil using only inf
Taxonomy vs function: Do functional groups exist and in a world of horizontal gene transfer. Do 16S sequ
The rare biosphere; waiting in the wings or ghosts in the machine?
There are many factors that alter and select which organisms belong in a specific environment, througho
To what extent are microbial species distributions influenced by climate? what would the consequences i
To what extent do microbial communities return to their "original" state after short-term perturbations?
To what extent does microbial community composition reflect functional redundancy in a habitat or ecos
To what extent is among human or animal variability in microbiome related to evolutionary processes occ

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- 2 To what extent is animal health and welfare influenced by their microbiome and does this have the poter
- 3 Universal sequence primers - can they ever exist?
- 4 What are the biggest gains in microbial ecology of the last decade and what are their implications for the
- 5 What are the consequences of antibiotic use in microbial communities in freshwater and soil environmer
- 6 What are the environmental hazards associated with bioremediation and biocontrol, and what can we dc
- 7 What are the likely impacts of climate change on plant diseases in understudied regions such as Africa, th
- 8 What are the links between microbial genomics and metabolomics?
- 9 What are the main biotic and abiotic determinants of population structure in microbial communities in w
- 10 What are the main mechanisms by which nutrients accumulated by saprotrophs are released to the envir
- 11 What are the major constraints on microbial life on land and water, and how do they differ?
- 12 What are the mechanisms by which the gut microbiota protects its host from pathogens?
- 13 What are the mechanisms used by mycoviruses to confer host fitness to its environment?
- 14 What are the microbial ecology consequences of the cultivation of exotic tree species?
- 15 What are the most successful applications of microbial ecology in the real world?
- 16 What are the opportunities to determine cause or effect relationships in microbiome studies?
- 17 What are the primary mechanisms that mediate microbial interactions within a host? and the strength of
- 18 What are the survival implications of skin and gut microbiomes of captive bred or head-started animals?
- 19 What are the traits of microbial species that are a) globally ubiquitous b) endemic to certain areas?
- 20 What can animal, human and plant health policy-makers learn from evolutionary ecology?
- 21 What effect will rising water levels have on coastal microbes and their diversity?
- 22 What is the 'functioning' of a microbial community?
- 23 What is the acceptable amount of disease in a healthy forest ecosystem?
- 24 What is the actual relevance of Black Queen Hypothesis
- 25 What is the average carbon footprint of a paper in microbial ecology and how can it be reduced?
- 26 What is the best method to assess the contribution of rare vs abundant species in a microbial community
- 27 What is the best strategy to control and stop waterborne outbreaks?
- 28 What is the best way of monitoring drinking water safety?
- 29 What is the ecological meaning of an OTU?
- 30 What is the ecological relevance of the internalization of bacterial pathogens by protozoa in terms of the
- 31 What is the importance of biotic vs abiotic characteristics in determining microbial community compositi
- 32 What is the importance of photosynthetic symbionts of larval amphibians?
- 33 What is the relative importance of inter- and intra-specific diversity in fungal communities?
- 34 What is the relative importance of stochastic vs. determinative processes in fungal community assembly?
- 35 What is the relative role of competition versus cooperation for microbial biodiversity
- 36 What is the role of bacteriophages in biofilm dynamics in natural environments?
- 37 What is the role of the microbiota in speciation processes?
- 38 What is the true link between diversity and function in an ecosystem?
- 39 What mechanisms are distinct in microbial ecology as opposed to conventional ecology?
- 40 What methodological processes do we need to develop to give a holistic view of microbial diversity and f
- 41 What methods can we use to marry microbial diversity with function, what role could proteomics play?
- 42 What new sequencing techniques do we need to improve our understanding of microbial ecology?
- 43 What new technologies are available to detect cross-feeders in an environmental sample?
- 44 What proportion of fungi carry endobacteria, and what effect does this have?
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2 What scales are appropriate for studying microbes?
3 What selection pressures does the modern world place on evolving microbes?
4 What technologies are needed to advance microbial ecology?
5 What's the best way to manipulate the microflora?
6 Which factors determine the host range of microbial pathogens?
7 Which factors determine the structure of gut microbiomes?
8 Which factors determine whether Wolbachia increases or decreases its host's susceptibility to pathogens
9 Which factors trigger 'covert' infections to become 'overt', impacting host health?
10 Which factors trigger the emergence of new microbial pathogens in humans and wildlife?
11 Which is the most effective way of disinfecting drinking water?
12 Why are some microbial pathogens often 'covert'?
13 Why do genomes contain redundant copies of genes
14 Will 16S rRNA be supplanted as the key phylogenetic identifier
15 Will fungal underrepresentation in the life sciences keep on decreasing as was the case over the last two
16 Will metagenomics ever supplant next generation sequencing?
17 Will metaproteomics ever become an important major methodology in microbial ecology?
18 Will microbes become commonly used as biological control agents of invasive alien plants in Europe?
19 Will ocean acidification or temperature increase provide the greatest selective pressure for microbial ma
20 Will the challenge of fungal genomics to the dogma of name-based biosecurity be taken on board by phy
21 Will the culturing of the other 99% of bacteria be possible with increasing understanding of syntrophy an
22 Will the flood of new papers on climate change and microbial ecology lead to increased specialization and
23 Will the use of network theory in plant epidemiology help prevent plant health emergencies such as Euro
24 Will there be substantial funding for research and management of tree diseases over the next decades, o
25 Will there ever be a cohesive species concept which applies to bacteria?
26 Will there ever be a unified V 16S rRNA region set of primers to capture total diversity
27 Will we be able to find new antibiotics in microbial species? Should we prioritise funding for this?
28 Will we ever be able to differentially monitor infective and non infective viruses in the environment?
29 With specific reference to non-model organisms. We know metazoa harbour a diverse array of microbial
30 With the amount of -omics sequence information coming out every week, how can scientists is it worth t
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tain genetic elements which are required?

an disinfected zones whereby resistant microbes have the potential to thrive and be pathogenic?

uropean Food Safety Authority?

is rife?

insight into adaptability?

roduction?

appens next?

icrobial population?

merging species in response to extreme changes?

t questions? For example, waste water bioremediation and carbon cycling.

n? Inversely, can current ecological theories inform us on microbial ecology?

i based techniques?

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ch the community is investigated?

pecies conservation?

? And will there be a way to measure absolute abundance using current sequencing methods?

rogenicity in other microbes?

industrial purposes?

t positive effects instead?

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2 diation?
3 apacities, genomes)?
4 ane, etc)? What are the implications of microbial species loss in these cycles?
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10 microbial communities or do this methods get bias from collecting too much material from dead
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22 oot, size of the whole tree, maturity of the tree?
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25 nunity in streams?
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27 r microbiota?
28 re presumably barophilic?
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31 n experimental artifacts?
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44 making bodies
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58 se â€˜big dataâ€™ projects?
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studies?

encing.

se conditions?
ising" and "enhancing"?

nunities which allows us to progress our understanding of what is structuring these communities

ns and therefore drinking water safety?

ersity and niche overlap?

of this?

rent places? What are the factors that affect this community most significantly?
ironments (e.g. seasonal, tidal, subject to frequent disturbance)?

ons of microbes?could new software improve on these limitations?

f microbiota of umbrella species?

the faecal matter of livestock and deposit on the land. What will be the long term effect on micro

effort into virus and microeukaryote ecology?

organisms?

is ecosystems (e.g. marine, freshwater, terrestrial, gut microbiota)?

are more easily published than negative ones) in microbial ecology?

biome environment?

effects?

studies of microbial ecology?

less on documenting diversity?

information about the abiotic factors of a soil?

ences mean anything?

ut the years we have established the importance of temperature, pH, moisture, basic factorsâ€¦

of any resulting microbiome shift for agriculture and biodiversity?

system?

curing within an individual's microbiome?

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2 ntial to affect conservation efforts?
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5 future of the field?
6 its and how they influence human health?
7 o to prevent them?
8 he Middle East and Central America?
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39 ir survival and spread?
40 on, and how does that influence ecosystem functioning?
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19 decades?

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24 rine organisms?

25 tosanitary regulators?

26 d the rise of metabolomic and transcriptomic studies

27 d communication problems within the field?

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29 pean ash dieback?

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31 r is the recent surge in the UK a short-lived burst?

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38 diversity. How can changes in microbial communities, either through changes in community com
39 he while for scientists to create alliances so this information can be quickly available for other sci
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For Peer Review

cells?

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5 microbial population as a driver for antibiotic resistance?
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which are the new most important factors that are of interest to microbial ecologists?

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position or microbial evolution, help long lived (annual +) animals adapt to rapidly changing environments that might be interested in the same information? Joining forces throughout societies.

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